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14. ABSTRACT
The objective was to realize a phase- and amplitude-stable, coherent atomic beam. The completed setup allows one to achieve this goal and contains: (1) a Zeeman slower as a primary cold-atom source, (2) a relay magneto-optic trap that collects and cools the atoms, (3) a pusher beam that transfers the atoms in bunches into a (4) magneto-optic injection device, (5) a 1.7m long magnetic atom guide section for continuous evaporative cooling, (6) a condensation and atomic-beam extraction region at the end of the guide, and (7) provisions to perform atom

15. SUBJECT TERMS
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Report Title

Continuous Magnetic Atom Guides

ABSTRACT

The objective was to realize a phase- and amplitude-stable, coherent atomic beam. The completed setup allows one to achieve this goal and contains: (1) a Zeeman slower as a primary cold-atom source, (2) a relay magneto-optic trap that collects and cools the atoms, (3) a pusher beam that transfers the atoms in bunches into a (4) magneto-optic injection device, (5) a 1.7m long magnetic atom guide section for continuous evaporative cooling, (6) a condensation and atomic-beam extraction region at the end of the guide, and (7) provisions to perform atom interferometry. Component (4) adiabatically compresses atoms and releases them into (5); it also includes a mechanical atomic-beam shutter for optical insulation of laser-cooling light from the magnetic-guiding section. In (5), the cold-atom flow is continuously cooled via surface adsorption on 21 silicon strips. Final status: Construction of all components and laser systems is complete. Components (1) - (3) have been experimentally tested. The components (4) - (7), while being ready to use, will require considerable human resources for continued work. The project has included a component on photo-ionization, Rydberg atom evolution, and spatially resolved ion detection in magnetic guides as an analytic method for position-resolved BEC and cold-atom imaging. The work on Rydberg guiding and ion detection is complete.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received	Paper
2012/01/18 1 5	R. R. Mhaskar, S. E. Olson, G. Raithel. Open-channel fluorescence imaging of atoms in high-gradient magnetic fields, The European Physical Journal D, (11 2006): 0. doi: 10.1140/epjd/e2006-00242-8
2012/01/17 1: 3	V. D. Vaidya, M. Traxler, C. Hempel, R. R. Mhaskar, G. Raithel. Ion imaging in a high-gradient magnetic guide, Review of Scientific Instruments, (04 2010): 0. doi:

TOTAL: 2

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

Presentation at the 2007 Midwestern Cold Atom Workshop at the University of Wisconsin, Nov. 3, 2007.

Seminar at Michigan State University (Sept. 27, 2007).

Seminar at Wayne State University (Oct. 23, 2008).

Seminar at Stevens Institute of Technology (Oct. 17, 2008).

Invited presentation at international Atom Laser conference, Les Houches, France (April 2010) http://www.irsamc.ups-tlse.fr/Atom2010/

Poster at DAMOP 2007 in Calgary, Canada (poster number D1 5).

Poster at DAMOP 2008 in Penn State: R1.00091 Progress towards a Continuous-Wave BEC

Contributed talk at DAMOP 2008 in Penn State: J3.00002 High-gradient Magnetic Guide for Rydberg Atoms

Contributions at DAMOP 2009 in VA:
E1.00090 Progress towards a continuous atom laser
S4.00007 Guiding and Trapping of Rydberg atoms in a linear magnetic atom guide

Contributions at DAMOP 2010 in Houston, TX
E1.00103 Continuous, guided atomic beams

Contributions at DAMOP 2011 in Atlanta:
T3.00006 Evolution of Rydberg atom clouds in a linear magnetic trap
U2.00007 Design for a compact CW atom laser

Number of Presentations: 13.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received		Paper
2012/01/18 1	6	M. Traxler, R. E. Sapiro, C. Hempel, K. Lundquist, E. P. Power, G. Raithel. Guiding of Rydberg atoms in a high-gradient magnetic guide, Physical Review (02 2012)
2012/01/17 1	1	V. Vaidya, M. Traxler , C. Hempel , R. Mhaskar, G. Raithel. Ion imaging in a high-gradient magnetic guide, Review of Scientific Instruments (01 2010)

TOTAL: **2**

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

APS Fellow (2007)

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Mallory Traxler	0.10	
Rahul Mhaskar	0.50	
Rachel Sapiro	0.20	
Cagalr Yavuz	0.10	
FTE Equivalent:	**0.90**	
Total Number:	**4**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Tara Liebisch	0.05
Rahul Mhashar	0.10
Rachel Sapiro	0.10
FTE Equivalent:	**0.25**
Total Number:	**3**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Georg Raithel	0.05	
FTE Equivalent:	**0.05**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Karl Lundquist	0.20	Physics
Varyn Vaidya	0.10	Physics
Cornelius Hempel	0.20	Physics
FTE Equivalent:	**0.50**	
Total Number:	**3**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	2.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	2.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	2.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	1.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	0.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	1.00

Names of Personnel receiving masters degrees

NAME	
Cornelius Hempel	
Total Number:	**1**

Names of personnel receiving PHDs

NAME	
Rahul Mhaskar	
Total Number:	**1**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

The objective was to realize a phase- and amplitude-stable, coherent atomic beam. The completed setup allows one to achieve this goal and contains: (1) a Zeeman slower as a primary cold-atom source, (2) a relay magneto-optic trap that collects and cools the atoms, (3) a pusher beam that transfers the atoms in bunches into a (4) magneto-optic injection device, (5) a 1.7m long magnetic atom guide section for continuous evaporative cooling, (6) a condensation and atomic-beam extraction region at the end of the guide, and (7) provisions to perform atom interferometry. Component (4) adiabatically compresses atoms and releases them into (5); it also includes a mechanical atomic-beam shutter for optical insulation of laser-cooling light from the magnetic-guiding section. In (5), the cold-atom flow is continuously cooled via surface adsorption on 21 silicon strips. Final status: Construction of all components and laser systems is complete. Components (1) - (3) have been experimentally tested. The components (4) - (7), while being ready to use, will require considerable continued human resources for actual demonstration of a continuous atom laser. The project has resulted in one paper on atom imaging in guides and one paper on ion imaging in guides. The project has included a component on photo-ionization, Rydberg atom evolution, and spatially resolved ion detection in magnetic guides as an analytic method for position-resolved BEC and cold-atom imaging. The work on Rydberg guiding and ion detection is complete, and one paper on this is close to submission.

See attachment for some details.

Technology Transfer

Continuous Atom Laser and Atom Interferometry in a Magnetic Atom Guide

W911NF-06-1-0292 (Agreement number)

50396-PH (ARO proposal number)

1. Introduction

The generation of a truly continuous, coherent, phase- and amplitude-stable beam of atoms is expected to herald a new era in the field of Atom Optics. The method we pursued is to generate a BEC and to continuously replenish it with pre-cooled thermal atoms, while simultaneously extracting a continuous, guided, coherent atomic beam. While the project has not been finished, an apparatus suitable to achieve the initial goals has been completed. The work has included considerable design efforts that address all problems that have been encountered during the work. Several other groups researching on similar goals have made similar progress, most notably a group lead by Dalibard and Guery-Odelin in France. To date, no truly continuous atom laser exists yet. Hence, that prize is still outstanding, and the research is worthy to be continued. The project has lead to several publications on partial results.

2. Setup design and construction

The core piece of the setup is a 1.5 m long magnetic atom guide formed by two current-carrying wires (current 300A) with 4 mm center-to-center separation. The wires are located inside a vacuum tube; the wires are hollow and water-cooled. We reach a field gradient of 3000 G/cm. Our simulations from an earlier project phase have shown that, in order to achieve cw atom lasing, the guide needs to be injected with a dense flow of about 3 x 10^9 Rb atoms per second at 100 μK. Our simulations, as well as simulations from the French group lead by J. Dalibard, show that continuous evaporative cooling along the entire length of the guide will lead to quantum degeneracy. The desired condition can be characterized as a mostly classical, near-hydrodynamic flow of a cold atomic gas column that is of order 1 meter long and several 100 microns in diameter. The collision length is on the order of the gas-tube radius, which is sufficiently short to allow for evaporative cooling and to provide heat insulation of the cold (BEC) from the warm (injection) end of the guide. On the other hand, the collision length is such that the core region of the atom flow is **not** thermally insulated from the cylindrical evaporative-cooling surface. Our tree-code simulations, performed by former graduate Spencer Olson on the project, have shown that a steady state can be achieved that has a negative forward temperature gradient and a phase-space density approaching unity. At this point, the classical treatment becomes invalid and the flow becomes quantum-degenerate. A stationary continuous BEC will form, if a 3D trapping point is provided at the cold end of the guide. To form a 3D trap, our design includes a thin light-shift barrier (532 nm light for Rb) near the end of the guide. A potential minimum, required as a reservoir for the continuous condensate, is formed by the strong transverse guiding potential, a gentle downward gravitational slope, and the light-shift barrier. To extract output from the BEC into the remaining (short) guide section beyond the light-shift barrier, the power of the laser forming the barrier is reduced to a point where a sustainable, tunneling-induced atom output current from the BEC is established. Since the output current is still magnetically guided, it is ideal for interferometric applications that are based on guided atomic beams. The current setup will allow for interference experiments on short scales (~1cm long).

An overview of the atom guide and loading system is shown in Figure 1. The injection of cold atoms into the guide obviously requires laser cooling light in the vicinity of the atom guide. One of the main challenges a truly continuous BEC machine faces is that stray light must be shielded from the magnetic-guide region, which is always on. We use a rapid, pulsed-loading scheme for the guide with an integrated beam shutter. The primary atom source is a Zeeman slower. Atoms are collected in a transfer-MOT, from which they are pushed into a magneto-optic injector co-aligned with the axis of the main atom guide. Adiabatic transfer and compression of the atoms into the high-gradient section of the guide, which is 1.5m long, is accomplished using a magnetic conveyor, which is about 15cm long. The conveyor acts as an atom valve that adiabatically merges new batches of atoms with the cold atomic gas that resides and slowly flows through the high-gradient section of the guide. Another important function of the injection unit also is that it mode-matches atom clouds picked up from the MOT + molasses region with the highly compressed cold gas in the guide section. The mode-matching is accomplished via adiabatic compression through a tapered guide segment. While the loading is pulsed, individual pulses quickly merge into a continuous flow once they are in the high-gradient section of the guide. The current control unit for the magneto-optic injector coils and conveyor coils (12 coils altogether) has been designed and built.

The conveyor action is visualized here: http://www.youtube.com/watch?v=DHXyEQuirxw.

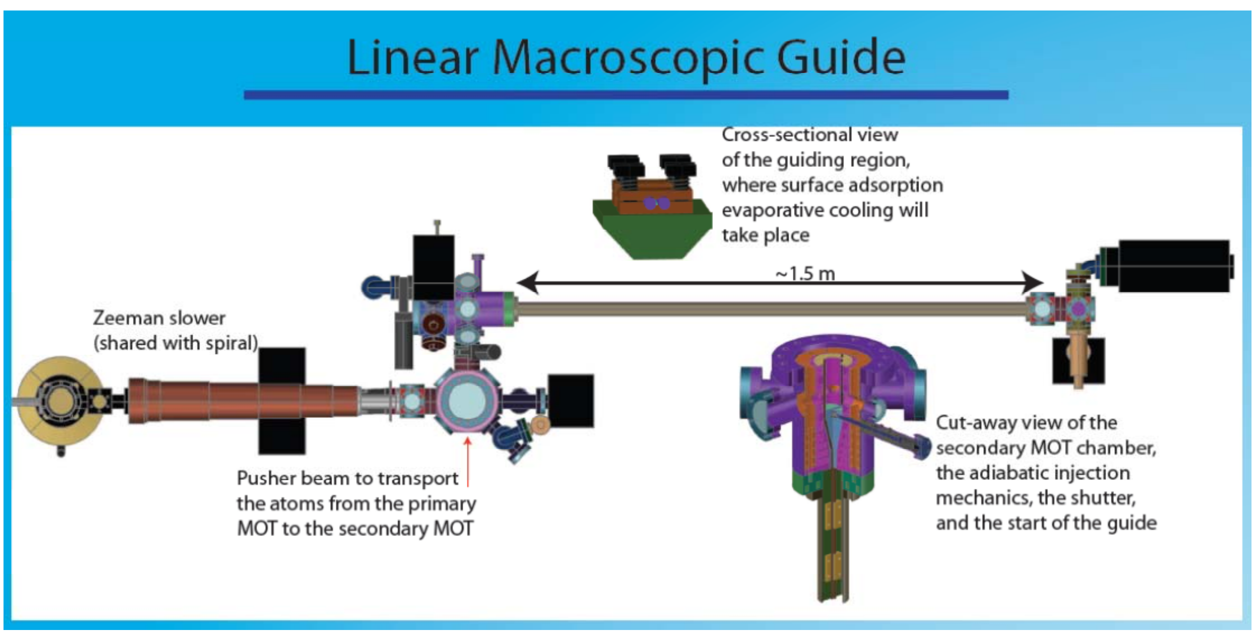


Figure 1: Overview over the guide system.

The completed allows for continuous cooling of the atom flow in the high-gradient section of the guide using surface adsorption on 21 5cm long silicon strips that are arranged along the guide axis. The principle of evaporative cooling via surface-adsorption, which has previously been demonstrated in E Cornell's group as an efficient method to prepare pulsed BECs [D. M. Harber *et al.*, Journal of Low Temperature Physics **133**, 229 (2003)], is ideal for continuous atomic-beam cooling because it replaces complex arrays of RF sources.

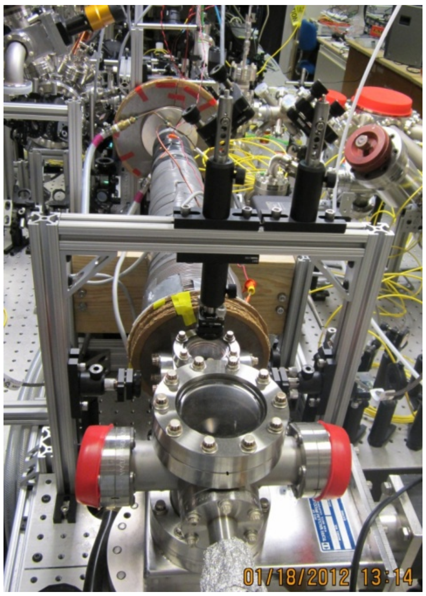


Figure 2a: View from the Zeeman slower towards the transfer-MOT, behind a magnetic-field shield with red tape strips, and the guide, located in the upper left of the picture.

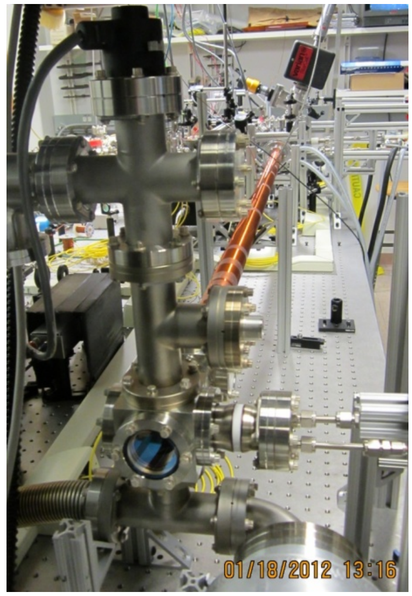


Figure 2b: View from the BEC region upstream along the guide. The guide tube carries a clearly visible copper solenoid that prevents spin-flip losses.

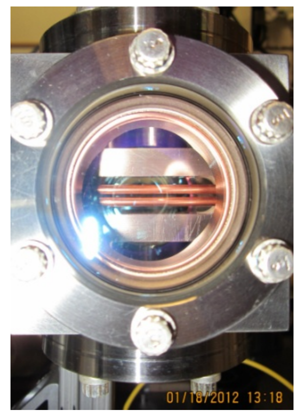


Figure 2c: View into the condensation region. The window has sufficient space for imaging and tunneling-barrier lasers.

The system was planned in detail and constructed by several undergraduate students and, on average, one to two graduate students in the lab. Many components of the setup, including the guide scheme, were copied from an earlier guide version. Along the high-gradient section of the guide we have mounted 21 precision-machined silicon strips for surface adsorption evaporative cooling. The magnetic injection device required considerable mechanical work, coil winding, and UHV-compatible gluing work. The atomic-beam shutter utilizes UHV compatible linear ball bearings and is mounted is a small-diameter vacuum side port, so that it can be magnetically actuated from outside the vacuum. The finished guide setup has been baked out, and the BEC end of the guide currently sits at 10^{-10} Torr, which is sufficiently low. The guide has been connected to a 400A power supply and a high-pressure water cooling loop that runs at 10 atmospheres. The vacuum compartment which holds the magneto-optic injection unit is heat-sunk with a water -cooled base plate (heat load up to several tens of Watts, low-pressure cooling loop). Most laser-cooling optics (MOTs, molasses and probes) have been set up. In Figure 2 we show upstream and downstream views of the complete guide system, as well as a view into the end port, where the continuous BEC is supposed to form. The work has included the setup of new cooling lasers (a master with 2W amplifier system), because an old critical unit had failed. We also have acquired a new 10W green laser to implement a narrow (~one micron thick) light-shift barrier at the end of the guide. The barrier is essential to (1) form a 3D potential minimum at the end of the guide, which functions as a reservoir for the continuous condensate, and to (2) extract atomic beam output through a continuous tunneling current into the guide region beyond the barrier. The work further included the design and construction of a 12-channel current control and amplifier unit that is capable of driving the 12 in-vacuum coils of the magneto-optic injection unit with arbitrary current waveforms.

More project information is posted at http://cold-atoms.physics.lsa.umich.edu/projects/cw-bec/ .

Given the massive amount of design and construction work, we view it as a great success that with the available resources we have propelled the project to the ready-to-use state it is currently at. Unfortunately, the work force in the lab was insufficient to proceed with science experiments on the new guide system. **The PI plans to submit a new proposed to the ARO with that goal in mind.**

3. Atom detection

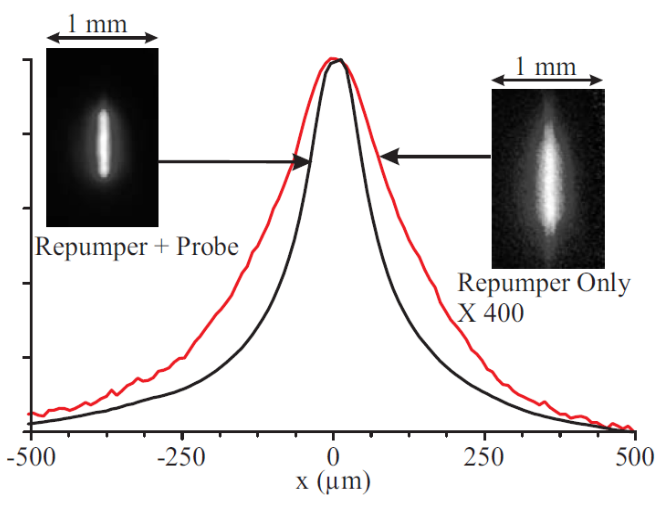


Figure 3: Comparison between a fluorescence image obtained on a closed-channel cycling transition, (black curve, left image) and an image obtained on an open transition (red curve, right image). The open-channel image is a true representation of the atomic-beam density profile whereas the closed-channel image is not.

The accurate imaging of atomic flows in strong, always-on guiding fields presents a substantial challenge because in most fluorescence probing schemes the position-dependent field-induced shifts as well as issues due the varying light polarization relative to the guiding field cause strongly position-dependent photon yield per atom. As a result, the conversion of fluorescence images into actual atomic-density becomes complicated and unreliable. In the early phase of this project, we investigated a method that allows for accurate imaging of distributions of cold atoms under the presence of large trapping-field-induced level shifts. By utilizing a probe laser tuned to an open transition, the fluorescence yield per atom is largely fixed throughout the trap volume, independent of the trapping field. This enables a reliable conversion of fluorescence images into atomic-density profiles. Two images that illustrate the difference between regular fluorescence imaging and open-channel imaging are shown in Figure 3. We applied the method to measure the distribution of ^{87}Rb atoms in our first-generation high-gradient atomic guide (2.7 kG/cm). We characterized the parameters for which the open-channel imaging method performs best. Quantum Monte Carlo simulations verified the underlying assumptions of the method. Results were published in “Open-channel fluorescence imaging of atoms in high-gradient magnetic fields,” R.R. Mhaskar, S.E. Olson, and G. Raithel, European Physics Journal **D 41**, 221–227 (2007).

4. Atom detection through photo-ionization

Atom ionization and spatially resolved charged particle detection has been shown to be a useful tool in imaging BECs [see, for instance, Gericke, T., Wuertz, P., Reitz, D., Langen, T. & Ott, H. Nature Phys. **4**, 949–953 (2008)]. In the context of probing atomic flows and BECs in atom guides, photo-ionization and subsequent spatially resolved ion imaging and counting are promising methods. These methods will allow for high-efficiency read-out in atom-interferometric devices. Since there are straightforward excitation schemes available that eliminate any photon scattering from intermediate atomic levels, stray-light-free performance can be implemented as needed.

To explore the applicability of the method in the present project, we studied photo-ionization and charged-particle imaging as a means to detect and image a narrow beam of cold atoms traveling along our high-gradient two-wire magnetic guide. Since the guide field is continuously on, electron detection would require prohibitively high acceleration voltages to be able to control the effect of the Lorentz force on the electron trajectories. In contrast, ion detection with the guide field on is fairly straightforward due to the heavy mass of the Rb ion. In the experiment, the ions were accelerated in a compact acceleration region, directed through a drift region several centimeters in length, and detected using a position-sensitive ion detector (see Figure 4). The potentials of several electrodes were varied to adjust the imaging properties. Using ion trajectory simulations as well as experiments, we studied the passage of the ions through the detection system, the magnification of the detection system, and the time-of-flight characteristics. Results were published in “Ion imaging in a high-gradient magnetic guide,” Varun Vaidya, Mallory Traxler, Cornelius Hempel, Rahul Mhaskar, and G. Raithel, Rev. Sci. Instr. **81**, 043109 (2010).

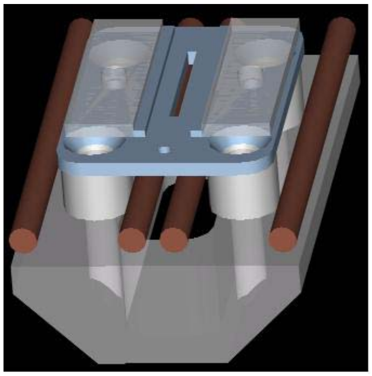
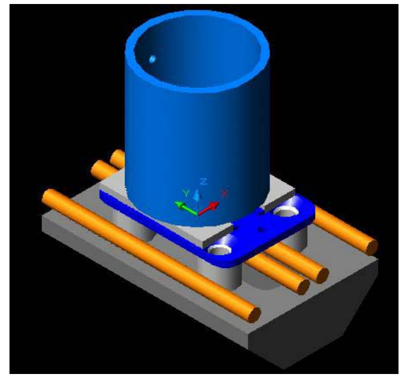


Figure 4: Atom detection unit based on photo-ionization. The unit utilizes a set of ion extraction electrodes (left), an ion-guiding tube (right), a micro-channel plate particle detector with phosphor screen, a pulse counter, and a CCD camera for image analysis.



5. Guiding of Rydberg atoms in a high-gradient magnetic guide

There has been a recent surge of interest in Rydberg atoms in cold, linear atomic systems. Such systems present the possibility of creating one-dimensional spin chains by exciting atoms into high-lying Rydberg levels, which interact strongly due to their large dipole moments. Rydberg crystals, which have been proposed in a frozen atomic gas using the Rydberg excitation blockade effect, may be an interesting application within a linear structure. Entangled Rydberg atoms prepared in a linear guiding geometry could act as a shuttle for quantum information. A one-dimensional trap or guide for Rydberg atoms could be used to further these types of research. Conservative trapping of Rydberg atoms in magnetic atom guides has been theoretically investigated by Schmelcher, Cederbaum and co-workers. The Rydberg-Rydberg interaction properties in such a system have also been studied theoretically.

In recent work, we employed our first-generation high-gradient guide to study, for the first time, the guiding of Rydberg atoms in a linear magnetic trapping geometry. Time delayed microwave ionization and ion detection was used to probe the Rydberg atom motion. We observed guiding of Rydberg atoms over a period of 5 ms following excitation. The decay time constant of the guided atom signal was found to be about five times that of the initial state. We attributed the lifetime increase to thermally induced Rydberg-Rydberg transitions and an initial phase of l-changing collisions. Detailed simulations of Rydberg atom guiding reproduced most experimental observations and offered insight into the internal-state evolution.

In some more detail, cold atoms confined in the steep transverse guiding potential are excited into Rydberg levels. In the image and the time trace shown below, 59D Rydberg atoms are initially prepared using a 20μs two-step excitation pulse (780nm + 480nm). The excitation point is near the center of the ion detection unit shown in Figure 4. The excitation occurs under (practically) electric-field-free conditions within the guide magnetic field. The subsequent evolution of the atoms is recorded using microwave ionization and ion imaging / counting. A sample result is shown in Figure 5. A manuscript on this work is about to be submitted [“Guiding of Rydberg atoms in a high-gradient magnetic guide," M. Traxler, R. E. Sapiro, C. Hempel, K. Lundquist, E. P. Power, and G. Raithel].

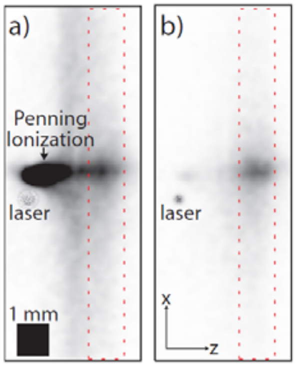


Figure 5: Image of Rydberg atoms initially prepared in 59D and detected after 1.5ms. (a) Camera on throughout the experimental cycle. The image contains signal due to initial Penning ionization, which lasts for several 100 microseconds after excitation, a widely dispersed signal component due to high-field-seeking Rydberg atoms being yanked out of the guide, and a concentrated core, within the red box, that is due to guided Rydberg atoms which become microwave-ionized after 1.5 ms of guiding. (b) To isolate the signal due to guided Rydberg atoms, the camera is gated over the microwave ionization pulse. In the mode, the image is dominated by the signal attributed to guided Rydberg atoms.

6. Technology transfer

Largely based on the experience gained through the ARO funded project, we have fabricated a high-atom guide on a 4-inch silicon chip. This work has been funded by the NGA and a DURIP from the AFOSR. The atom chip has been completed (see Figure 6) and mounted in a UHV vacuum chamber. The system is baked out connectorized with infrastuctiure needed to load it with cold atoms. The PI plans to include upcoming physics research on the chip guide in a future proposal to the ARO.

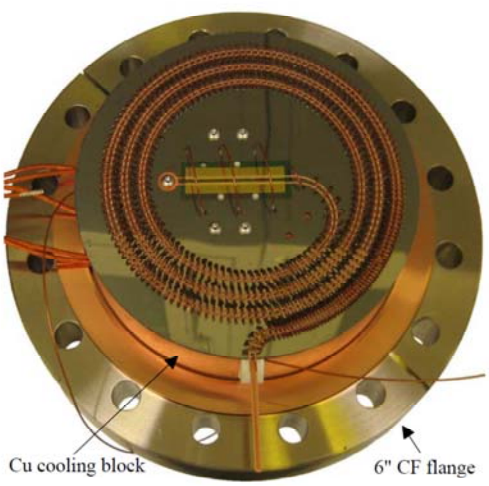


Figure 6: Spiral-shaped atom-guide chip mounted on a copper block and a 6" CF flange (picture taken before assembly of the UHV system). The atom guide is surrounded by a toroidal-like solenoid that prevents spin flips of atoms in the guide. The center region of the chip is prepared for several types of atom interferometers.